DEVELOPMENT OF A WHIPLASH INJURY REDUCING SEAT SYSTEM USING BIORID II DUMMY

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ABSTRACT

In recent years, several kinds of seat systems that aim to reduce cervical spinal injuries in rear impacts, so called 'whiplash injuries', have been released by some car manufacturers and seat suppliers in the world. Meanwhile, several kinds of dummies have been developed to be representatives of occupants under such conditions. One of these is the BioRID II equipped with a realistic spine constructed of multiple vertebrae similar to that of a human. It is regarded as the most biofidelic dummy for low speed rear impact. Using this dummy, some typical 'whiplash protective' seat systems currently available were dynamically tested to see their performance on injury reduction. From the results of these tests, the design direction to lessen the injury level more efficiently was determined. According to this direction, such parameters as the position of the head restraint and the force-deflection characteristic of the seat back were optimized by means of computer simulation with an in-house developed dummy model. These optimizations made on the existing seat system resulted in lower injury levels in the dynamic tests. In this study, injury levels were estimated mainly by means of Neck Injury Criterion (NIC) currently proposed as the only quantitative criterion based on the hypothesis of spinal ganglion injury. In addition, the upward acceleration at the top of the thoracic spine (T1) that might be one index for injury that was based on the hypothesis of 'synovial fold impingement' caused by the upward motion of the torso was taken into account.

INTRODUCTION

'Whiplash injury', that is cervical spinal injury in low speed rear-impact car accidents, is the most frequent injury that leads to a great deal of societal cost, especially for medical and insurance. In Japan, traffic statistics data [1] show rear impact accidents from 1990 to 1999 have increased by 63% while the other car-to-car accidents have increased by 27% during the same decade. In 1999, rear impact occupies 35% of total car-to-car accidents. Insurance data [2] show 56.7 percent of injuries in rear impacts are cervical spinal injuries. In the US, neck injury was reported in 66% of all bodily injury insurance claims in 1992[3]. Such injuries cost at least $7 billion a year [4]. To reduce these numbers of injuries, some car and seat manufacturers in the world in recent years have developed their particular seat systems which are called 'whiplash protective' seat systems [5],[6],[7]. However, there is no authorized methodology to estimate 'whiplash protectiveness' of these seat systems. They were evaluated in their respective ways with surrogates, i.e., dummies or human volunteers, with various test speeds and injury criteria.

In this paper, some particular seat systems named as 'whiplash protective' are tested under equal conditions and evaluated by the same criterion. Based on the results for them, considerations are made which way is most efficient both for protection and production feasibility. Finally, some prototypes were built and tested to prove the methodology.

ESTIMATING METHOD

Zuby, et al [8] presented in detail their test procedure and results estimating the performance of some 6 production vehicles for whiplash protection. Basically the similar procedure to this was adopted here.

Test Dummy

Some dummies have been developed to be surrogates for low speed rear-impacted occupants. TRID neck [9] has more realistic articulation and extension characteristic than those of HYBRID III. Davidsson, et al [10] introduced BioRID P3 dummy which was instrumented with a 24 segment spine which could represent the kinematics of a human's cervical, thoracic and lumbar spines at low speed rear impact (Fig.1). Gotou, et al [11] showed the excellent biofidelity of BioRID P3 dummy, rather than HYBRID III with TRID neck or THOR, comparing to human volunteer tests at low speed(V=9.2km/h). Further, Gotou, et al [12] demonstrated the difference between behaviors of BioRID P3 and HYBRID III at higher speed (V=15 and 25km/h). Alhough, because of a risk of injury, no volunteer test was done to be compared to these high severity tests, it should be possible to assume Bio-RID P3 is more biofidelic than other dummies even at higher speed up to V of 25km/h. Therefore, the BioRID II that is the commercially available version of the dummy, changed negligibly from P3, was adopted in this study.
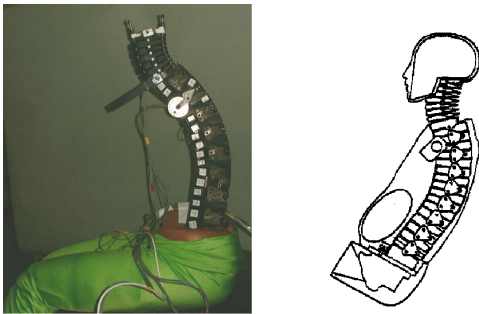

Fig.1 Bio-RID II dummy

Injury Criterion

The injury mechanism of 'whiplash' has not been proven, but some hypotheses have been proposed. Ortengren, et al [13] hypothesized whiplash injury was induced by membrane leakage in spinal ganglion nerve cells by a series of experiments using pigs. Bostrom, et al [14] illustrated these phenomena by fluid dynamics and came to the NIC (Neck Injury Criterion) which is calculated from the relative horizontal velocity and acceleration of the head and the T1(the top of the thoracic spinal vertebrae) as,

$$NIC = 0.2v_{rel} + a_{rel} \quad \text{--------- (1)}$$

where, v_{rel} and a_{rel} are the relative horizontal velocity and acceleration of the head and the T1. Eichberger, et al [15] and Wheeler, et al [16] tried to validate the NIC against the actual occurrence of injuries on human subjects, i.e., volunteers and PMHSs. From these results, the NIC value of $15m^2/s^2$ appears to be a safe threshold for long-term injuries.

Meanwhile, Ono, et al [17] took notice of the motion not only of the cervical but of the whole spine which was straightened during the impact causing the ramping-up motion of the torso and inducing the axial compression force on the lower cervical spine that resulted in the 'synovial fold impingement'. Though some parameters such as the axial neck force and the upward acceleration (Gz+) of T1 are thought to relate this mechanism, however, no quantitative evaluation has been made yet, and the axial neck force at lower cervical spine is currently not measured. Therefore, in this study, the NIC value is mainly adopted to estimate the relative 'whiplash protectiveness' of each seat system. The $Gz+_{max}$ value of T1 is compared to each other as a reference.

Test Method

HYGE sled pulses were tuned to be equivalent to those of car-to-car rear impact tests performed by Zuby, et al [8]. Based on the theory of impact, the velocity change of the impacted vehicle in a car-to-car test equals that of the vehicle impacting a rigid barrier with half the initial velocity of the impacting vehicle of a car-to-car test. Therefore, the average pulse was taken from some bumper to barrier tests and was provided as the target pulse of the sled.

Accelerations of the center of gravity (c.g.) of the head and of the T1 were measured to calculate the NIC value.

The test set up is shown on Fig.2. A seat was

anchored to the table of the sled. The angle of each seat back was adjusted to be equal to each other, and the dummy was set basically according to the procedure of NCAP or FMVSS 208. Each set of three uniaxial accelerometers was installed on the head and on the T1 to measure X, Y and Z accelerations for each. Head accelerometers were installed at the center of gravity of the head and each was laid on the X, Y and Z axis of the local coordinate system of the head. The head was set so that the X axis was horizontal before the test. T1 accelerometers were installed near the C7-T1 pivot on the extension bar that was fixed on the T1 to measure its angle. The extension bar was adjusted horizontal before the test and the X accelerometer was laid in this direction. The locations of these are shown on Fig.3.


Fig.2 Test set up of the HYGE sled
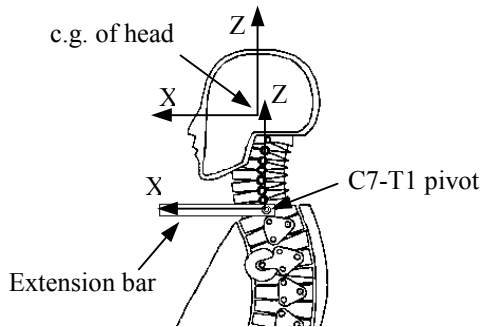
Fig.3 The locations and directions of accelerometers on the head and the T1
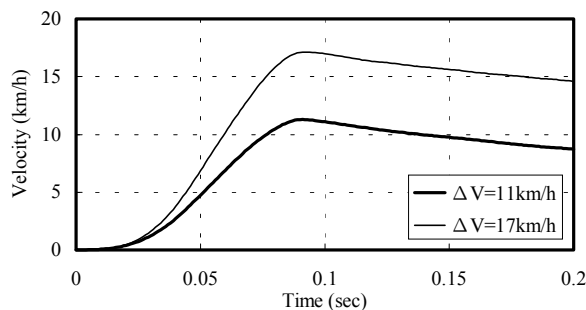
Fig.4 Velocity changes of HYGE sled tests

Test Velocity

The velocity changes (ΔV) applied to the sled tests were set to 11 and 17km/h(Fig.4) that are equivalent to the initial velocities of 10 and 15miles/h at car-to-car tests and approximately correspond to 50 and 80 percent of the frequency of rear-impact accidents reported by Eichberger, et al [18](Fig.5). Fig.5 was drawn by re-analyzing, that is, smoothing their data.
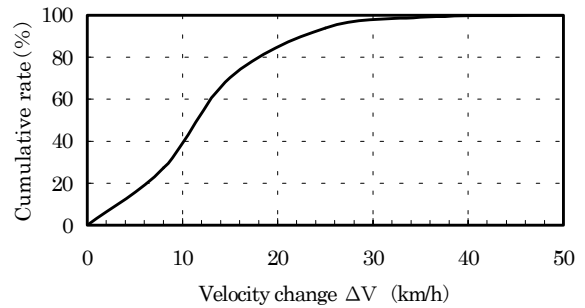
Fig.5 Distribution of velocity change in rear impact accidents redrawn from Eichberger, et al [18]

COMPARISON OF PERFORMANCE OF PRODUCTION SEATS

Three typical types of production seats that advocate 'whiplash protective', shown in Table.1, were tested. These seats have their particular features of construction that are oriented to reduce whiplash injuries as depicted in Table.1. The advantage of each type of seat is demonstrated in each paper [5],[6],[7] by the stated criteria and test methods.

These seats were tested with both velocity changes of 11 and 17km/h, and NIC values were calculated using measured local X accelerations of the head and the T1 after filtering with channel classes 1000 and 18 of SAE J211, respectively. The maximum NIC (NIC_{max}) values are shown on Fig.6.

Assuming the NIC value of 15(m^2/s^2) as a provisional standard here, all types of seats resulted in lower values than that at ΔV of 11km/h, while only type C did so at 17km/h.

The maximum upward Gz values ($Gz+_{max}$) of T1 filtered with channel class 180 of SAE J211 are shown on Fig.7. At delta V of 11km/h , the order is similar to that of NIC_{max}, while at 17km/h, type A shows the lowest value.

Table.1 Types of seats tested

Type	Feature
A	The location of the head restraint, the stiffness of the seat back frame and the force-deflection characteristic of the seat back cushion are optimized.
B	Equipped with the active head restraint moving forward when the occupant's back pushes the seat back
C	Equipped with the energy absorbing system at the recliner hinge
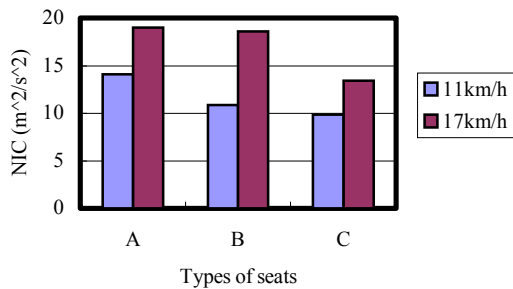
Fig.6 NIC$_{max}$ values of 3 types of seats tested
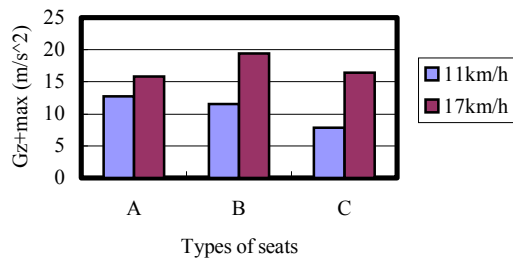
Fig.7 Gz+$_{max}$ of T1 values of 3 types of seats tested

CONSIDERATION FOR MODIFICATION

Based both upon the results for these 3 types of seats and on the investigation of the feasibility of them for production, the direction of modification was considered. Though type C shows the best performance of the three, it requires significant structural changes on existing normal seats. Type B shows better performance than type A at lower velocity, but seems equal at higher velocity, even though it is equipped with the extra parts of the active device. And looking at Gz+$_{max}$ of T1 values, it can be seen that the ramping-up motion of the torso is better controlled in type A at higher velocity. After these considerations, modifications in the similar direction to type A, that is, no additional devices but optimizations of some features in the normal seats were tried. These modifications were examined by means of simulation and component tests before building prototypes to be tested.

Base-line Analysis

From the result of one of the tests, the factors that affect the NIC$_{max}$ value were investigated by analyzing the acceleration pulses. As shown on the equation (1), NIC$_{max}$ is determined by both a_{rel} and v_{rel} depicted on Fig.8. It is clear that to minimize NIC$_{max}$ value is to minimize a_{rel} and/or v_{rel}. The characteristics to achieve it may be summarized as follows.

(1) To make head acceleration rise earlier
(2) To make T1 acceleration rise later
(3) To reduce the magnitude of T1 acceleration until NIC$_{max}$ is calculated

Some methods to enable the above characteristics into a prototype seat are listed in Table.2.

Optimization of the combination of these methods was tried.
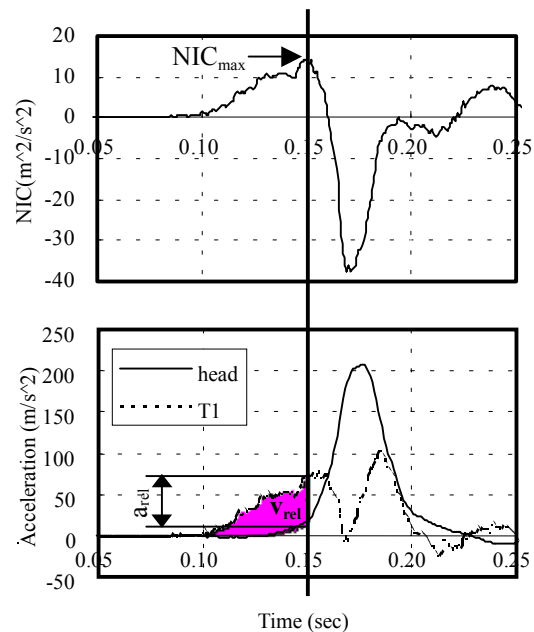
Fig.8 Illustration of the relation between NIC and accelerations of head and T1

Table.2 Methods to realize characteristics (1) to (3)

| Characteristic	Method
(1)	To set the head restraint forward
	To prevent folding back of the seat back
(2)	To soften the cushion of the seat back
(3)	To avoid bottoming of the back to hard structures inside seat back

Simulation

Because the dummy was under development, there was no simulation model for public use. Though Eriksson[19] developed the model based on a three dimensional rigid body technique, it was not made available to the public. Therefore, Sano, et al [20] developed a three dimensional model based on rigid body techniques as shown on Fig.9, but using FEM solver PAM-CRASH[TM][21] for future combined simulations with a three dimensional seat model fully modeled with solid elements. With this model, some parametric studies were made.
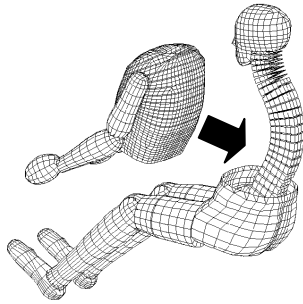
Fig.9 Configuration of the simulation model

First, the effect of the backset location of the head restraint was examined. As shown on Fig.10, the location of head restraint was changed forward and backward from the location of a normal seat by 10mm increments.
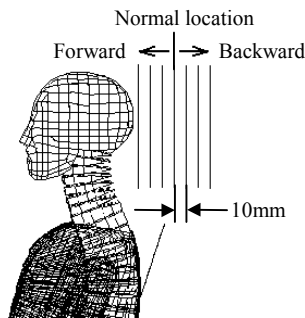
**Fig.10 Changes of the location of head restraint on the simulation**

Changes of calculated NIC_{max} Values are plotted on Fig.11. From the result, setting the location of the head restraint forward seems to be effective to reduce NIC_{max} value. In cases where the distance between the head and the head restraint becomes greater than some magnitude, no changes are seen. This is because the head restraint is located so that the head acceleration caused by the contact between the head and the head restraint rises after NIC_{max} occur.
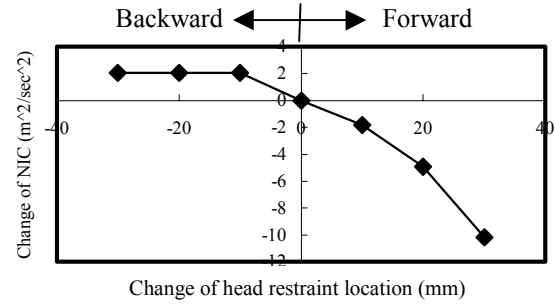
**Fig.11 Change of NIC_{max} value according to the location of head restraint**

Second, the effect of the location where the force from the seat back acts on the dummy's back on the NIC value was studied. The contact between the dummy's back and the surface of the seat back is defined for each vertebra by means of 'segment-to-plane contact'. In this type of contact, the force is calculated from the penetration of each segment into the corresponding plane with each force-deflection function defined. In this study, the force-deflection function is specified based on the data from the test of a seat back pressed statically with a known sized rigid surface. An obtained curve was then corrected according to the ratio of the areas of this pressing surface and each surface estimated as an effective surface of each segment-to-plane contact.

To look into the effectiveness of the location, the definition of the contact between each vertebral segment and seat back was removed by turns (Fig.12) and calculated NIC values were checked. The changes of NIC values from the basis are plotted on Fig.13.
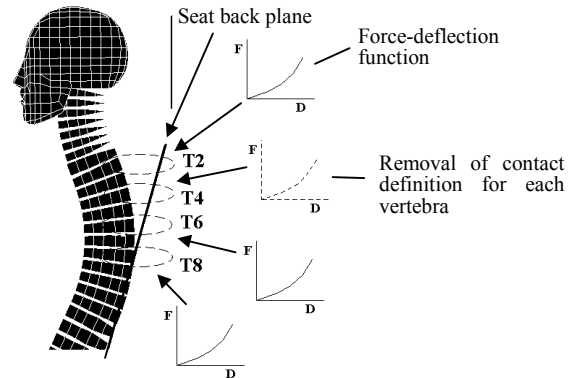
**Fig.12 Contacts between vertebrae and a seat back**

From the result, it appears that the location around T8 is more effective than the higher area. This means the optimization of the force-deflection characteristic should be made particularly on the cushion around the area T8 might contact.
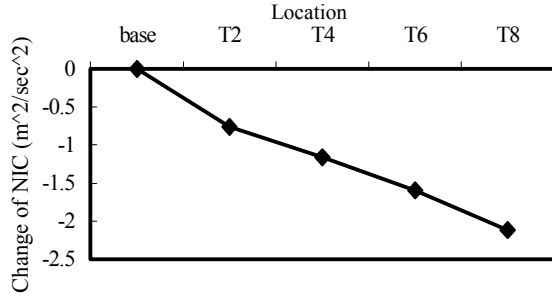
Fig.13 Change of the NIC$_{max}$ value when the contact definition was removed from each location of vertebral segment

Component Tests

To produce the required characteristics of a seat back cushion, component tests of the seat back including recliner hinge were performed. As shown on Fig.14, a seat assembly was fixed to a flat floor, and a seat back was pressed with the wooden block modeled on the shape of an AM50 percentile dummy's back. Using such a block that has similar curvature to the thoracic spine of the BioRID II is appropriate because the most effeciive area around T8 coincides with the deepest penetrating area of the block. The force was applied horizontally and the displacements were measured at two points, i.e., one on the block(X_1) and the other on the frame of a seat back(X_2) at the same height. From these two curves, the whole displacement can be divided into the deflection of the cushion and that caused by the inclination of the frame.
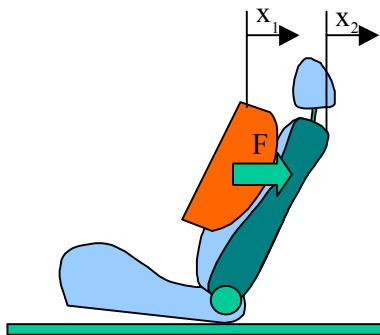

Fig.14 Aspect of component test

First, the normal seat was tested. Then some modifications were made considering three points as follows;
(1) Softening the cushion
(2) Enlarging the area where the back may sink into
(3) Keeping distances between hard structures inside a seatback and the occupant's back
This seat is called the prototype 1 (Proto 1). The test results of the normal seat and Proto1 are shown on Fig.15 to 17 compared with type A. X3 on Fig.17 means deflection of the cushion calculated by (X1-X2). Proto1 appears to achieve similar characteristics to type A on the whole displacement(X1).
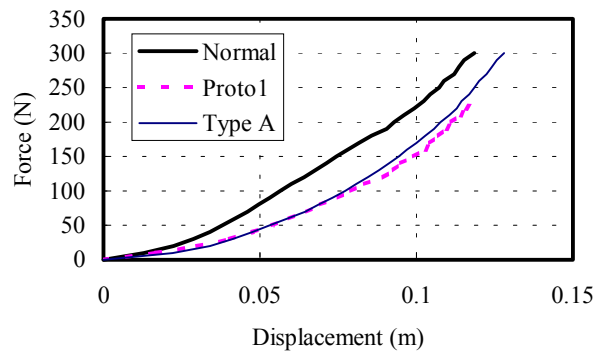
Fig.15 Force-displacement(x1) curves
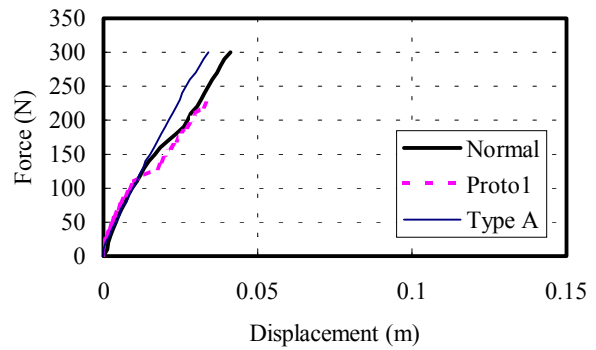
Fig.16 Force-displacement(X2) curves
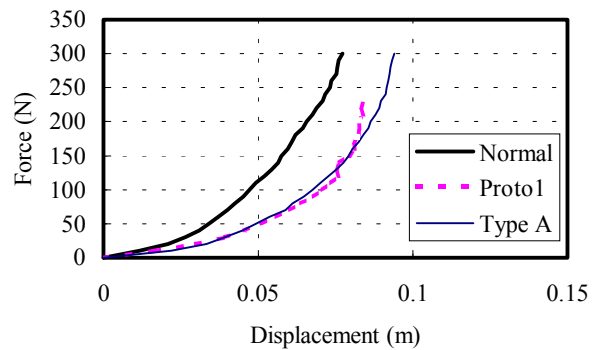
**Fig.17 Force-displacement(X3) curves**

The prototypes for the sled tests were then built following this result.

PROTOTYPE TESTING

Although it is obvious the location of the head restraint should be close to the head to reduce the NIC value, it can sacrifice the comfort of passengers if too close. With consideration to minimize the discomfort of passengers, the head restraint was moved as far forward as possible. Proto 1 seat was instrumented with the head restraint at this location and tested dynamically at two velocities.

The NIC values at Vs of 11 and 17 km/h are 11.4 and 16.1m^2/sec^2 respectively. These values mean such modifications described above on the location of the head restraint and on the characteristics of the seat back are effective enough to perform as well as types A and B.

Further modifications were made to see if it was possible to achieve the performance of type C at the higher velocity. Acceleration pulses of the head and the T1 were analyzed. These pulses are shown on Fig.18 and 19 compared with those of the normal seat and type A seat. Although the first peak value of the acceleration of the T1 which affects the NIC$_{max}$ is smaller than those of both the normal and type A seats, the time the acceleration of the head rises is little earlier than that of the normal and is still later than that of type A seat. Then, high-speed video analysis was carried out to see the phenomena around the head and the head restraint. Initial distance between head and head restraint (d$_1$) and displacement of head restraint until contacted by head (d$_2$) are read from high-speed image. Travel distance of head until contact (d$_3$) is equal to sum of d$_1$ and d$_2$ as shown on Fig.20.
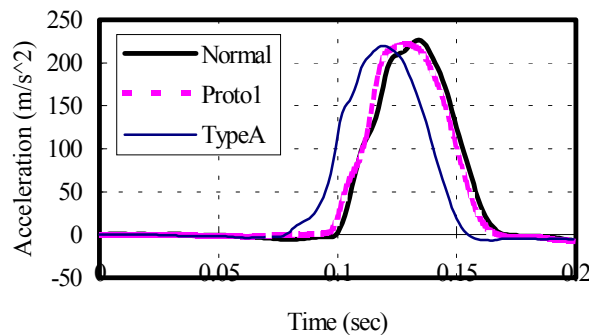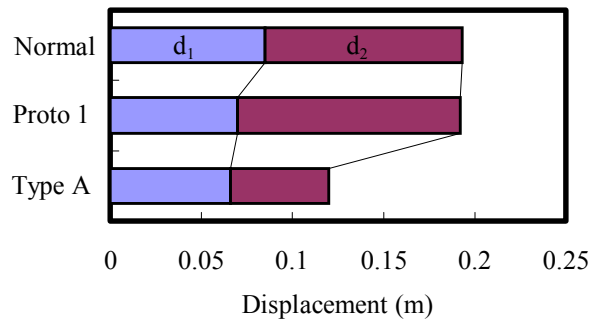

Fig.18 Acceleration pulses of head (1)
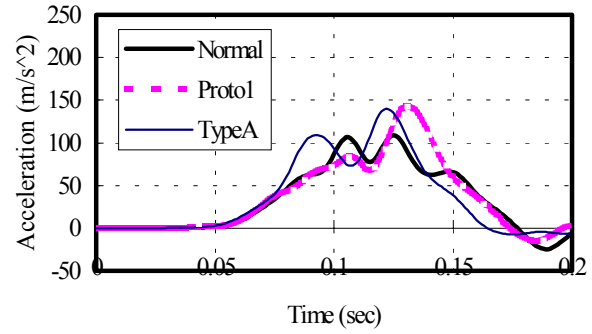
Fig.19 Acceleration pulses of T1 (1)
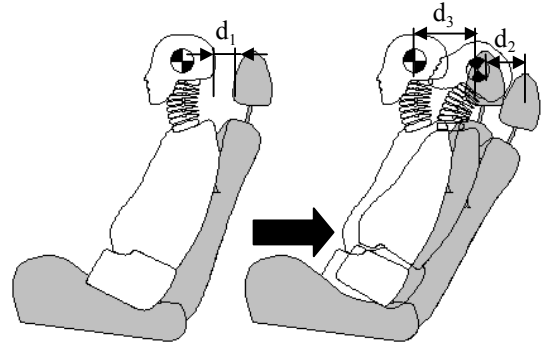

Fig.20 Illustration of d$_1$, d$_2$, d$_3$

Fig.21 Travel distance of head until contact (d1+d2)

Obtained values of d1 and d2 are shown on Fig.21. Though the head restraint was set forward for Proto 1, its displacement of the head is only little decreased from that of the normal seat. This means an expected effect of the head restraint set forward is cancelled by its own going away caused by the folding back of the seat back. Looking back at the results of component tests (Fig.15   17), even though the whole force-displacement (X1) characteristic of Proto 1 looks similar to that of type A, breakdowns, X2 and X3 appear to be different. Beyond the force of 100N, the cushion comes harder and the frame begins folding.

This means at the deflection around 0.075m of the cushion, a kind of bottoming out happens by some hard structure inside the seat back. Therefore, further modifications were made on Proto 1 seat to remove such bottoming, and it was named Proto 2.

Proto 2 seat was dynamically tested at two velocities as in the previous tests. Acceleration pulses of the head and the T1 at Δv of 17km/h are shown on Fig.22 and 23 compared with those of Proto 1. The head contacts earlier as expected and the acceleration level of the T1 doesn't rise too high until the contact of the head and the head restraint. Calculated NIC_{max}s are shown on Fig.24. Proto 2 seat achieved lower NIC values than other 'whiplash protective' seats at both velocity changes. $Gz+_{max}$ values of T1 shown on Fig.25 are also better controlled than other seats.
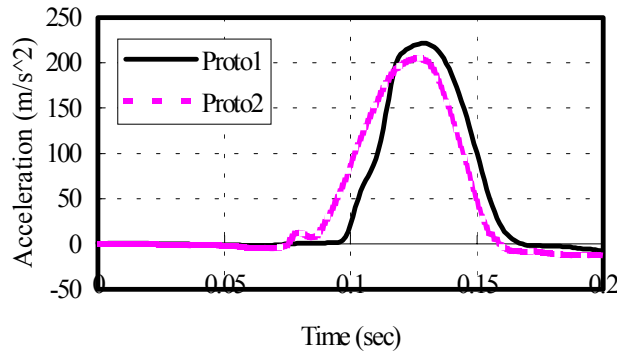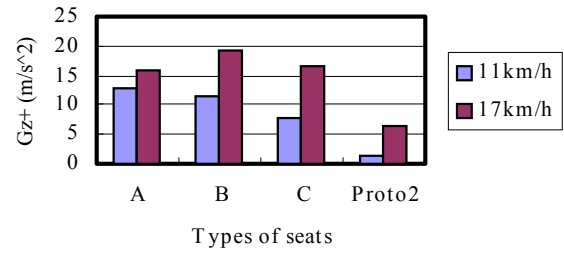

Fig.22 Acceleration pulses of head (2)
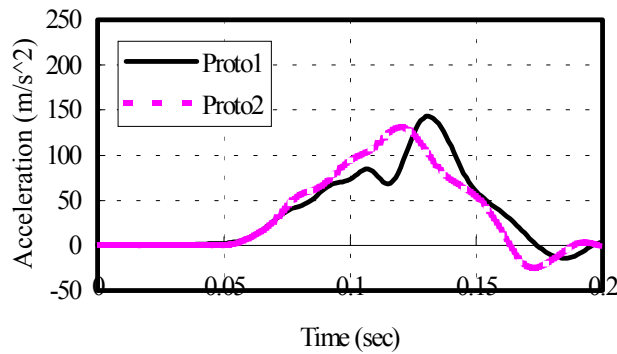
**Fig.23 Acceleration pulses of T1 (2)**
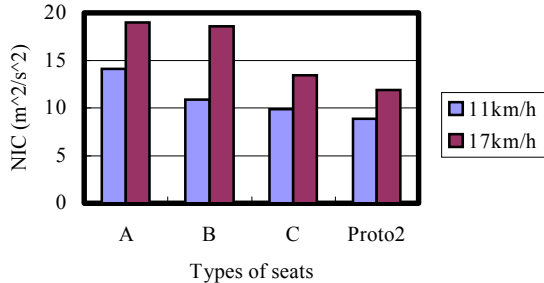
Fig.24 NIC_{max} values of Proto 2 and other seats

Fig.25 $Gz+_{max}$ values at T1 of Proto 2 and other seats

DISCUSSION

Though a method to reduce the values that are candidates to estimate the risk of 'whiplash injury' was made possible, the effect of it is difficult to prove in the real world. One reason for this difficulty may be that 'whiplash injury' has an aspect of psychological injury. That means the injury is without obvious physical symptoms but with pains felt by the patient caused only by the fact that he/she was struck[22]. However, analyzing the data from the real world rear-end crashes[23], it is obvious the relative location of the head and the head restraint, i.e., backset, affects the frequency of long term (≧1 week) injury. The statistical analysis was tried on these data using the SAS program[24]. The risk curve of long-term injury as shown on Fig.26 was assumed versus the parameter of backset(p=0.0005). This suggests the possibility of reduction of long-term injuries in the real world accidents by optimization of locations of head restraints. If the correlation between NIC and backset can be assumed, it can be said lower NIC may lead to lower long-term injury risk in the real world.
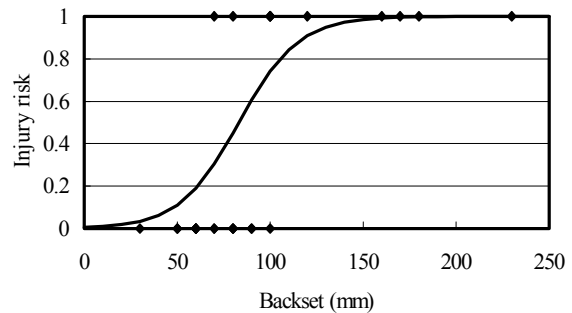
Fig.26 Assumed risk curve of long-term injury versus backset

CONCLUSIONS

A prototype seat succeeded in improving performance on 'whiplash protection' measured by NIC using the BioRID II dummy. Not only NIC_{max} but also the $Gz+_{max}$ value of T1 that may indicate the risk of 'synovial fold impingement' was consistently reduced.

Through the study, some reductions in NIC_{max} were realized with no additional devices but only with modifications on an existing seat. The three principal points of the modifications are as follows;

(1) To locate the head restraint as close to the head horizontally as possible to make head acceleration rise earlier, while keeping comfort of a passenger.

(2) To soften the seat back cushion around the contacting height with T8 to make T1's acceleration rise gently

(3) To remove hard structures inside the seat back that may cause bottoming when the dummy's back fully compresses the cushion in order both to avoid folding of the seat back and to control the peak level of T1's acceleration until head to head restraint contact

The knowledge above may be the fundamentals based on which actual seats aiming at the reduction of cervical spinal injuries in low speed rear-impact car accidents in the real world can be developed.

ACKNOWLEDGEMENT

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